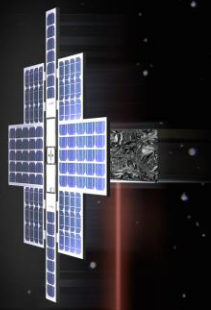

CubeSat multi-band optical receiver for the Lunar Flashlight mission

Frankfurt, Germany- 17 May 2018

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Outline

1 Introduction

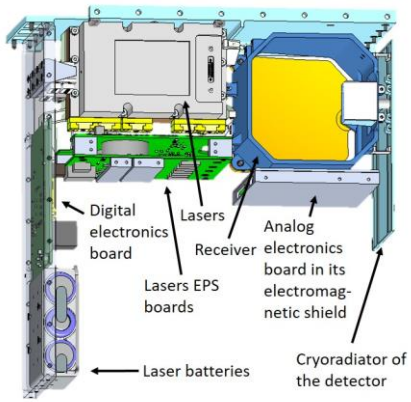
2 Instrument operation principle

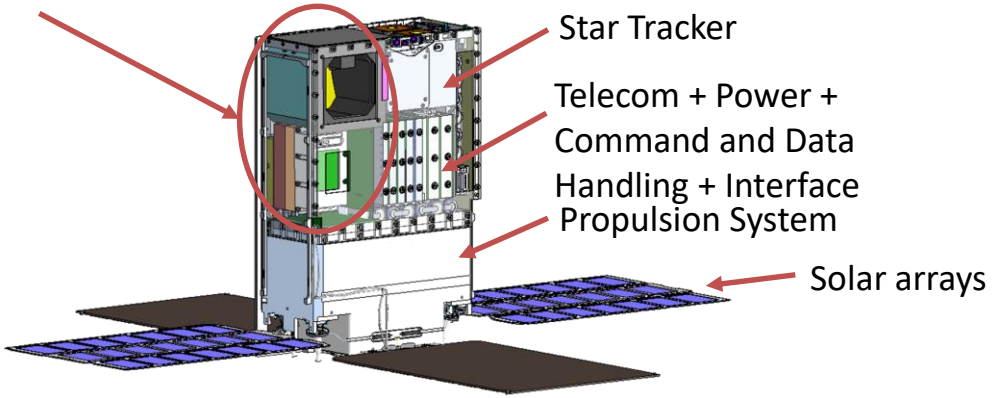
3 Receiver optomechanical design

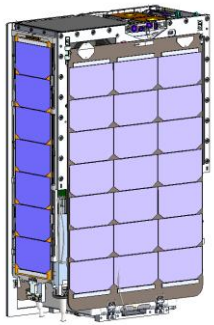
4 Conclusions and perspectives

- ***NASA Strategic Knowledge Gaps***: concentration and distribution of lunar volatiles, in particular water.
- ***Background***: strong indications of the presence of water ice in the Permanently Shadowed Regions (PSRs) of the lunar South Pole [1-4].
- ***Lunar Flashlight goals***:
  1. measure water ice concentrations on the lunar South Pole above 0.5 weight %
  2. map water ice distribution with a resolution of 1-2 km
- ***How*** : multi-band reflectometry from orbit.

Instrument: SWIR laser reflectometer

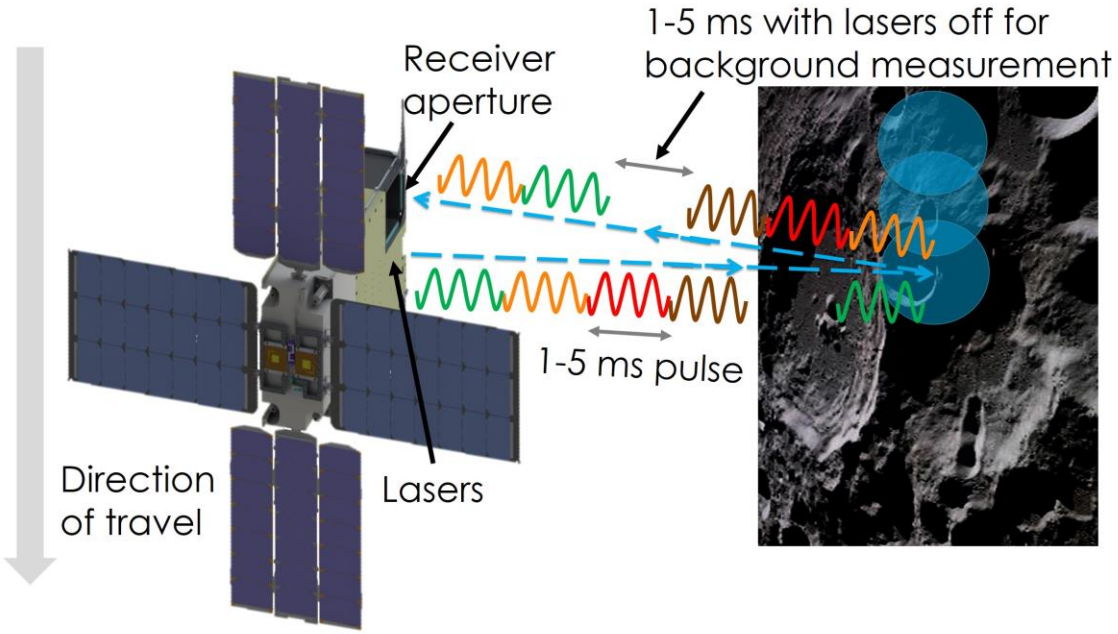


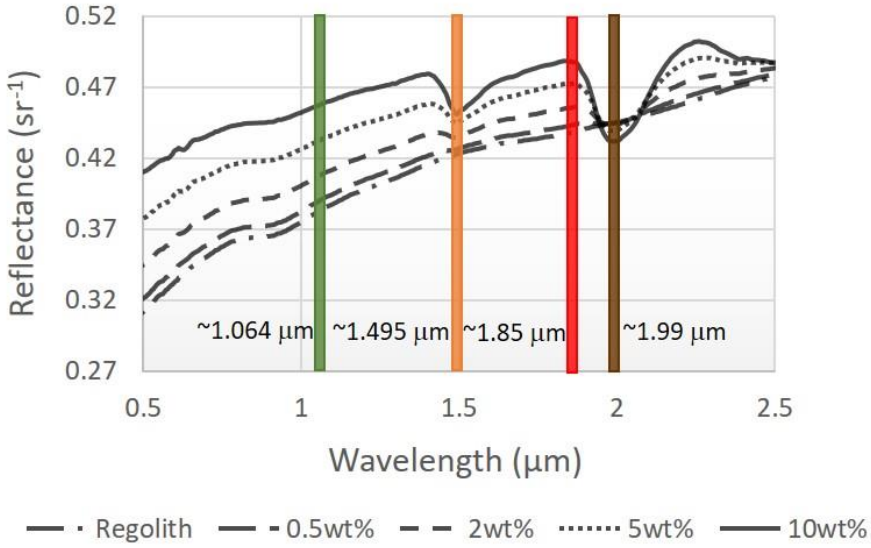




[1] Hayne, P. O. et al., "Evidence for exposed water ice in the Moon's south polar regions from Lunar Reconnaissance Orbiter ultraviolet albedo and temperature measurements," Icarus 255, 58-69 (2015).
[2] Thomson, B. J. et al., "An upper limit for ice in Shackleton crater as revealed by LRO Mini-RF orbital radar," Geophysical Research Letters 39(14) (2012).
[3] Schwadron, N. A. et al., "Signatures of volatiles in the lunar proton albedo," Icarus 273, 25-35 (2016).
[4] Fisher, E. A. et al., "Evidence for surface water ice in the lunar polar regions using reflectance measurements from the Lunar Orbiter Laser Altimeter and temperature measurements from the Diviner Lunar Radiometer Experiment," Icarus 292, 74-85 (2017).

Instrument operation principle

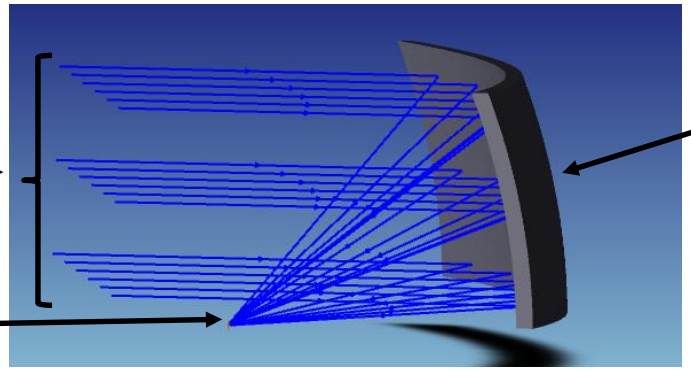




[5] Cohen, B. A. et al., "Payload Design for the Lunar Flashlight Mission," Proc. Lunar and Planetary Science Conference 48, 1709 (2017).
[6] Vinckier, Q. et al., "System Performance Modeling of the Lunar Flashlight CubeSat Instrument", Proc. Lunar and Planetary Science Conference 49, 1030 (2018).

Receiver optomechanical design

Receiver concept:



Design phases:

1. Selection of the mirror focal length and the detector active area diameter
2. Stray light analysis to minimize the background

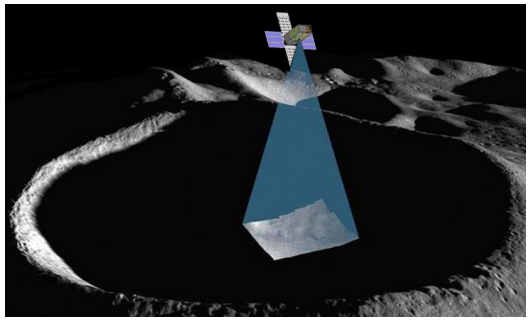
Optical design

3. Mechanical design

Receiver optomechanical design

Mirror Focal Length (FL) and diameter (Ø) of the detector active area :

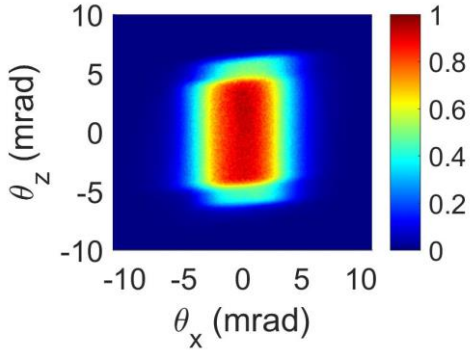
$$FOV = 2 \times arctan\left\{\frac{\emptyset}{2 \times FL}\right\}$$

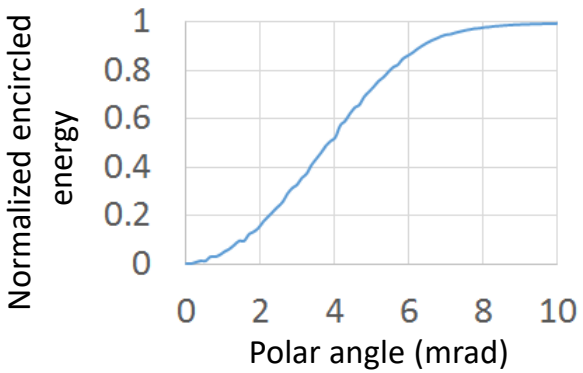


Driven factors:

- Maximization of the lasers' photons detection efficiency

Laser beams divergence profile

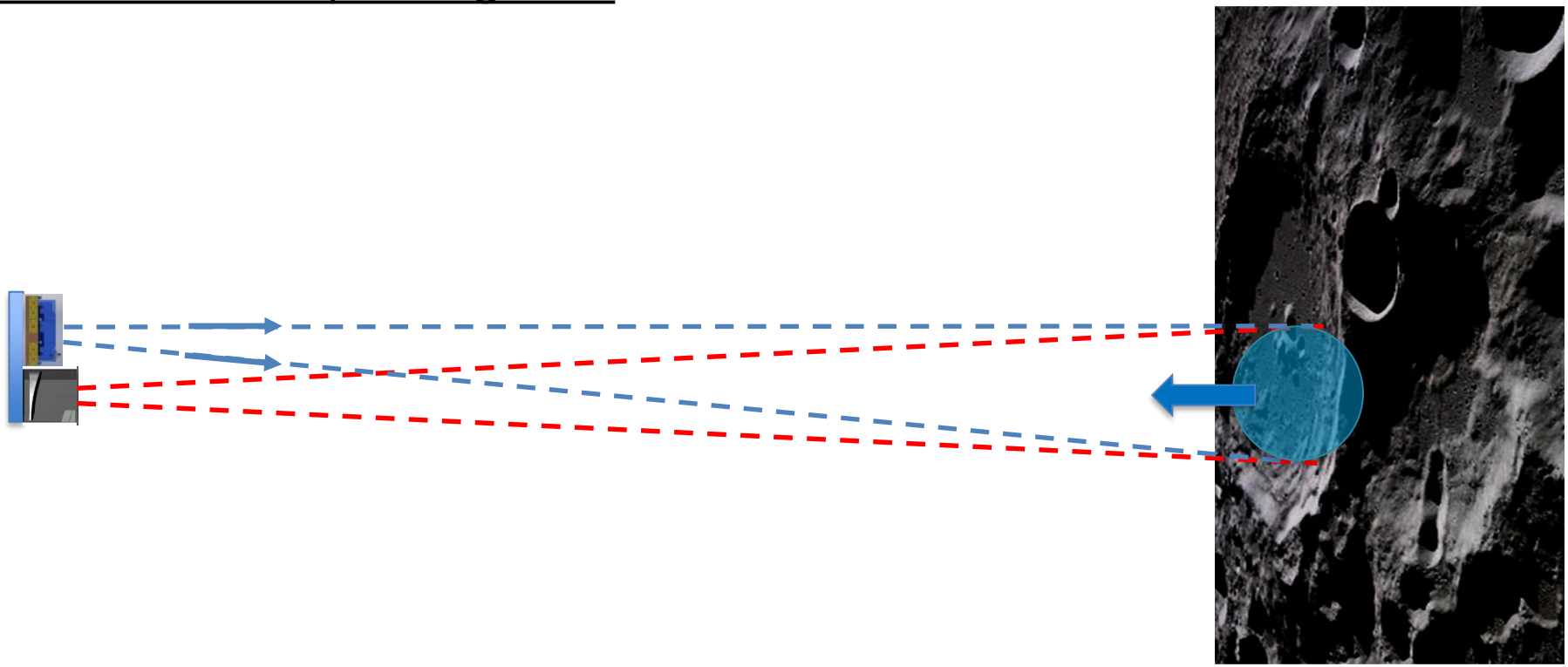




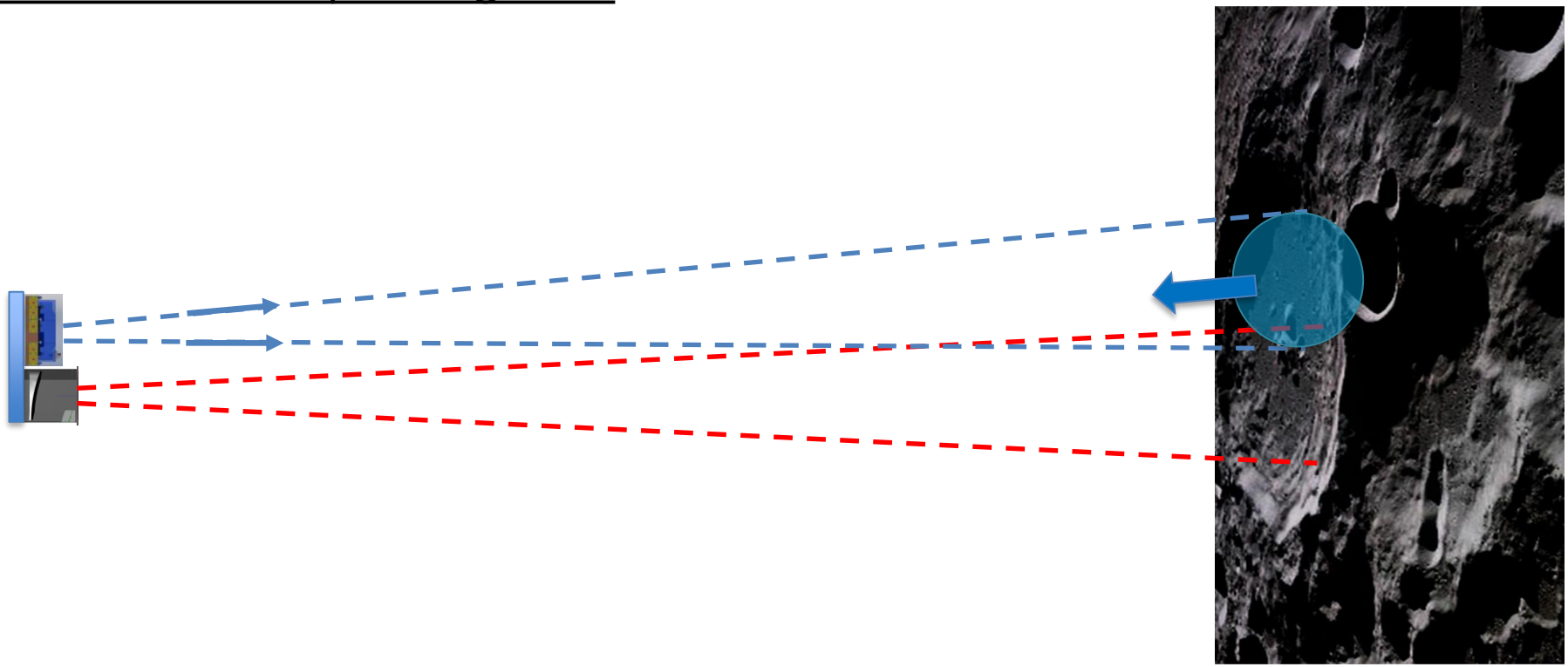
- Minimization of the detected solar illumination of the Moon surface (background)
- FOV margins to accommodate the laser-to-receiver pointing error budget

Receiver optomechanical design

Laser-to-receiver pointing error

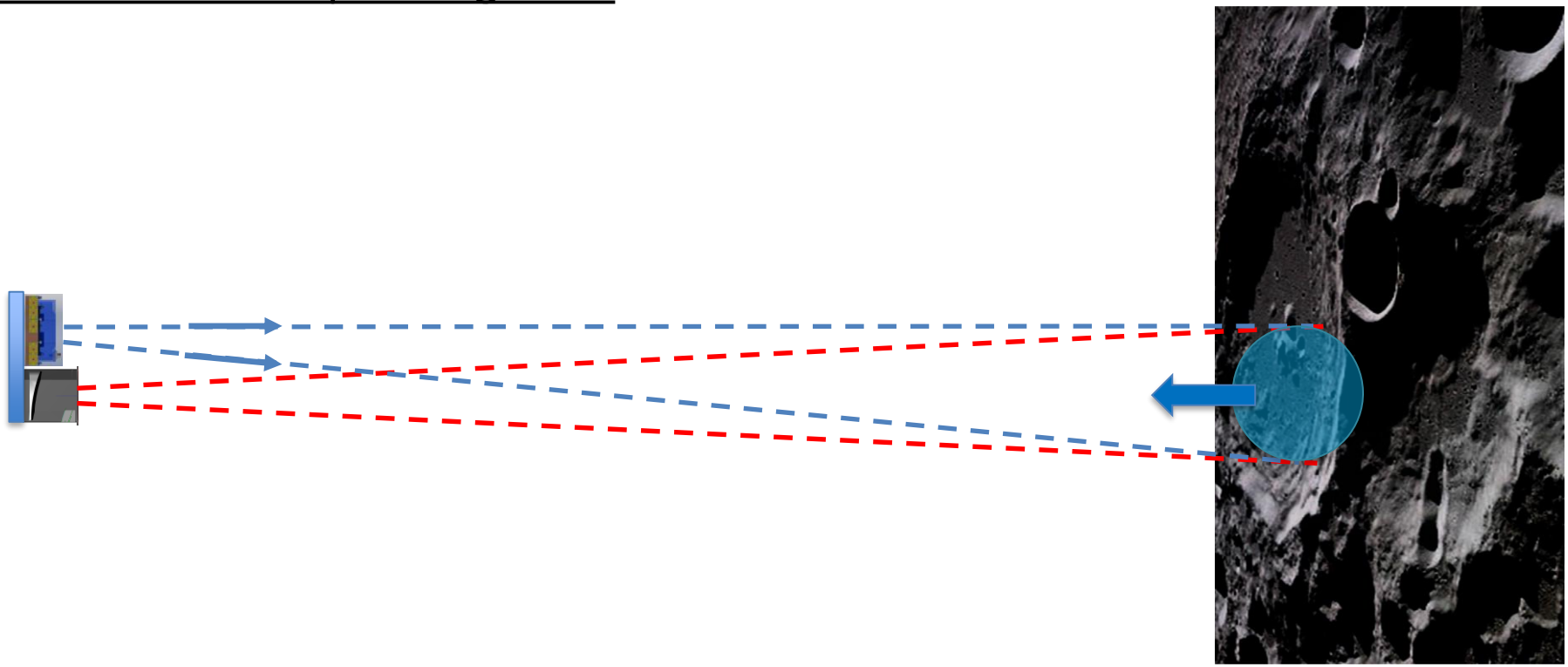


Laser-to-receiver pointing error



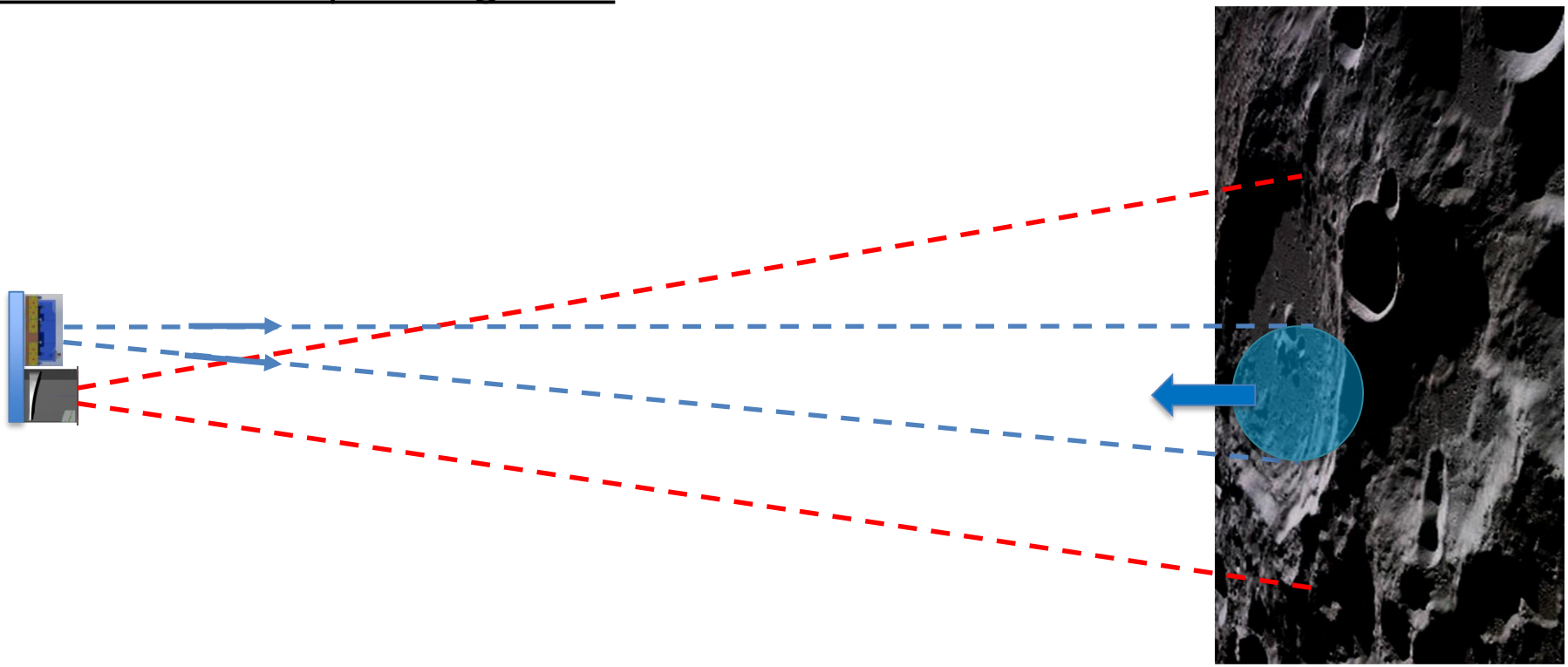
Receiver optomechanical design

Laser-to-receiver pointing error

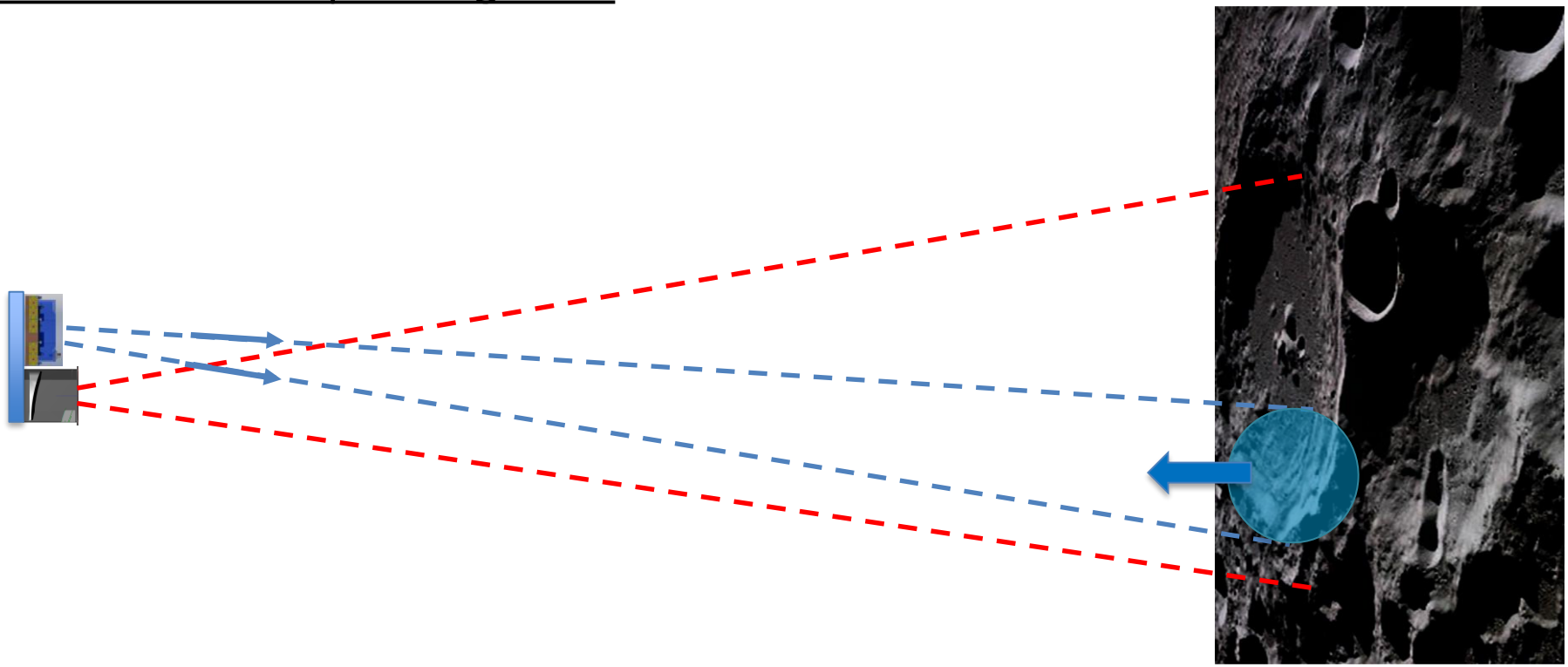


Receiver optomechanical design

Laser-to-receiver pointing error

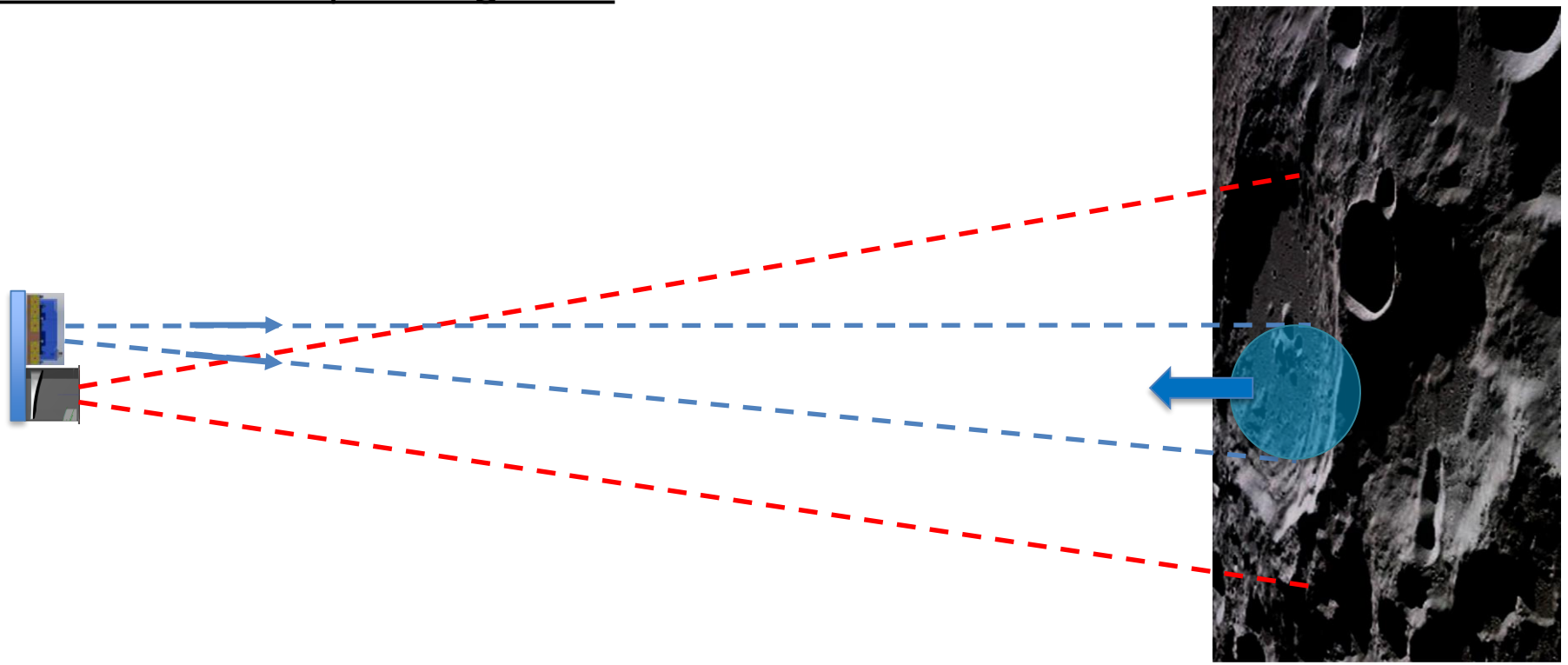


Laser-to-receiver pointing error



Receiver optomechanical design

Laser-to-receiver pointing error



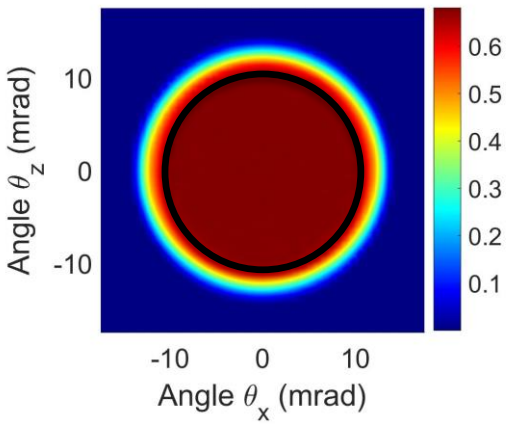
Our design:

$\emptyset = 2\ mm$

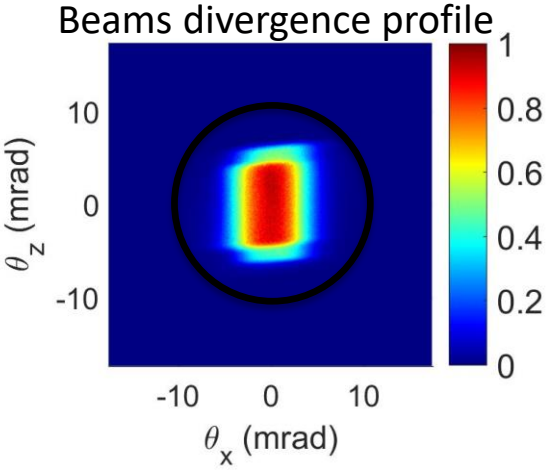
$FL = 70\ mm$

$FOV = 20\ mrad$

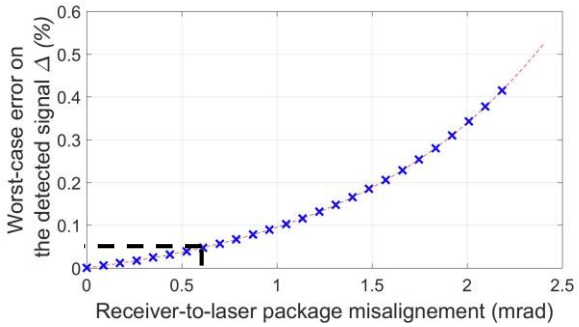
Receiver 2D PST



Beams divergence profile



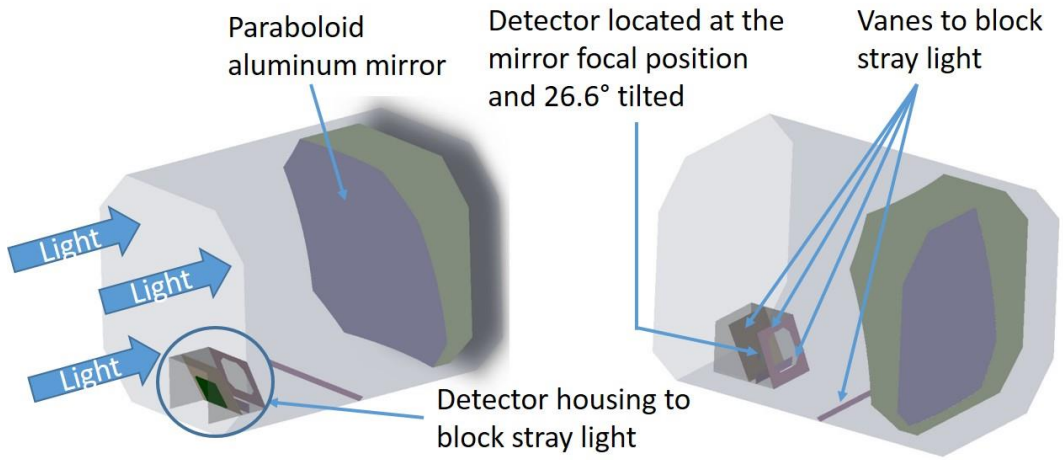
Estimated lasers-to-receiver pointing error during operation: 0.6 mrad

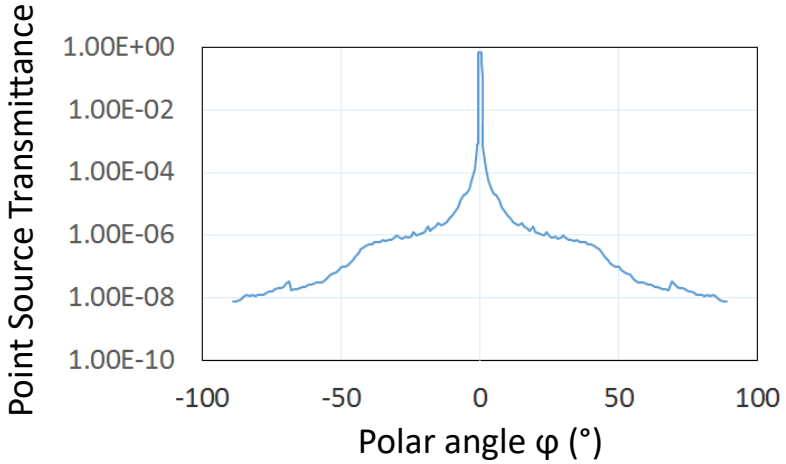


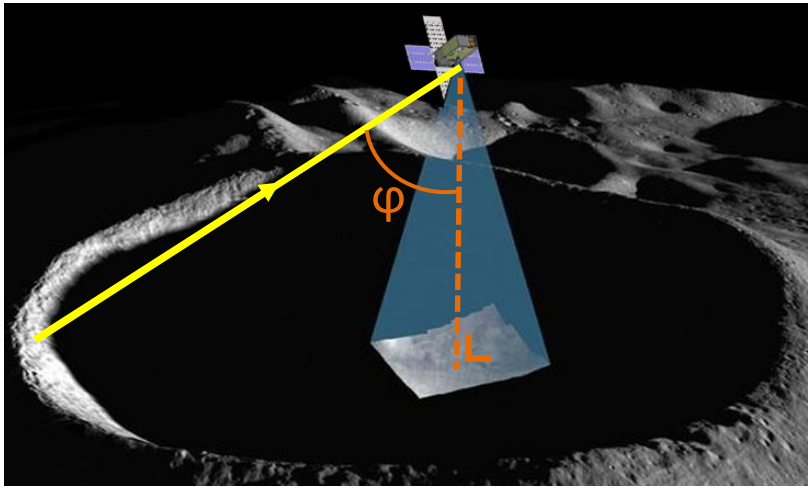
Receiver optomechanical design

Stray light analysis:

- *Goal:* Minimization of the detected solar illumination of the Moon surface outside the receiver FOV
- *Optical design:*

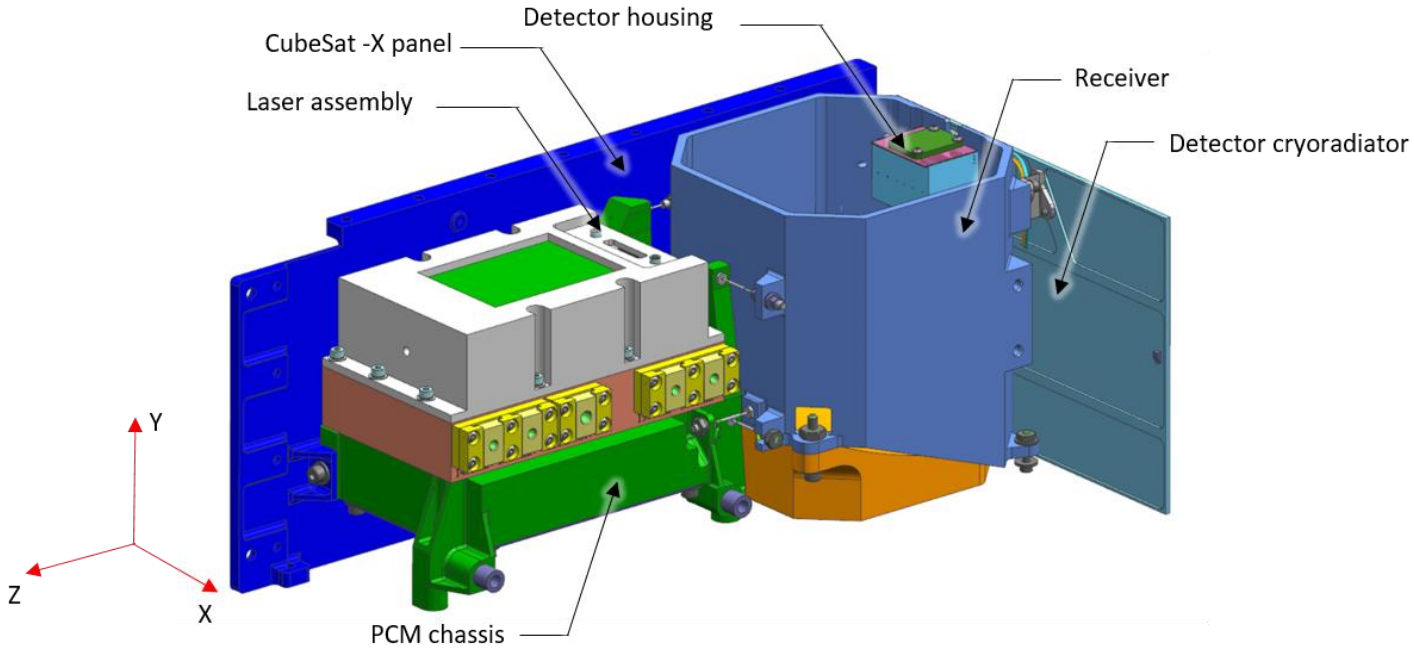


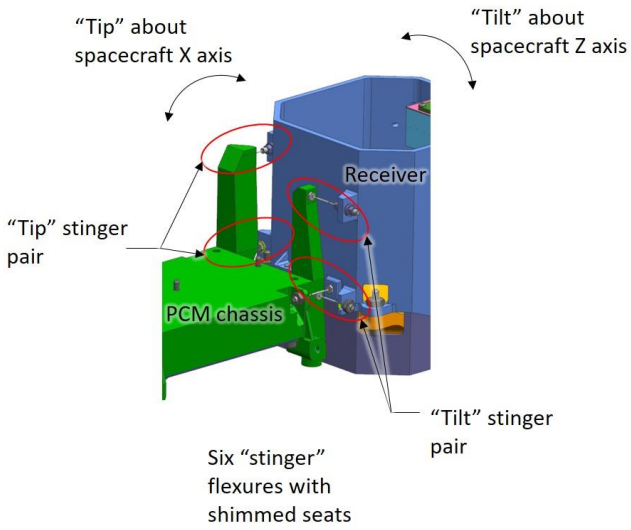




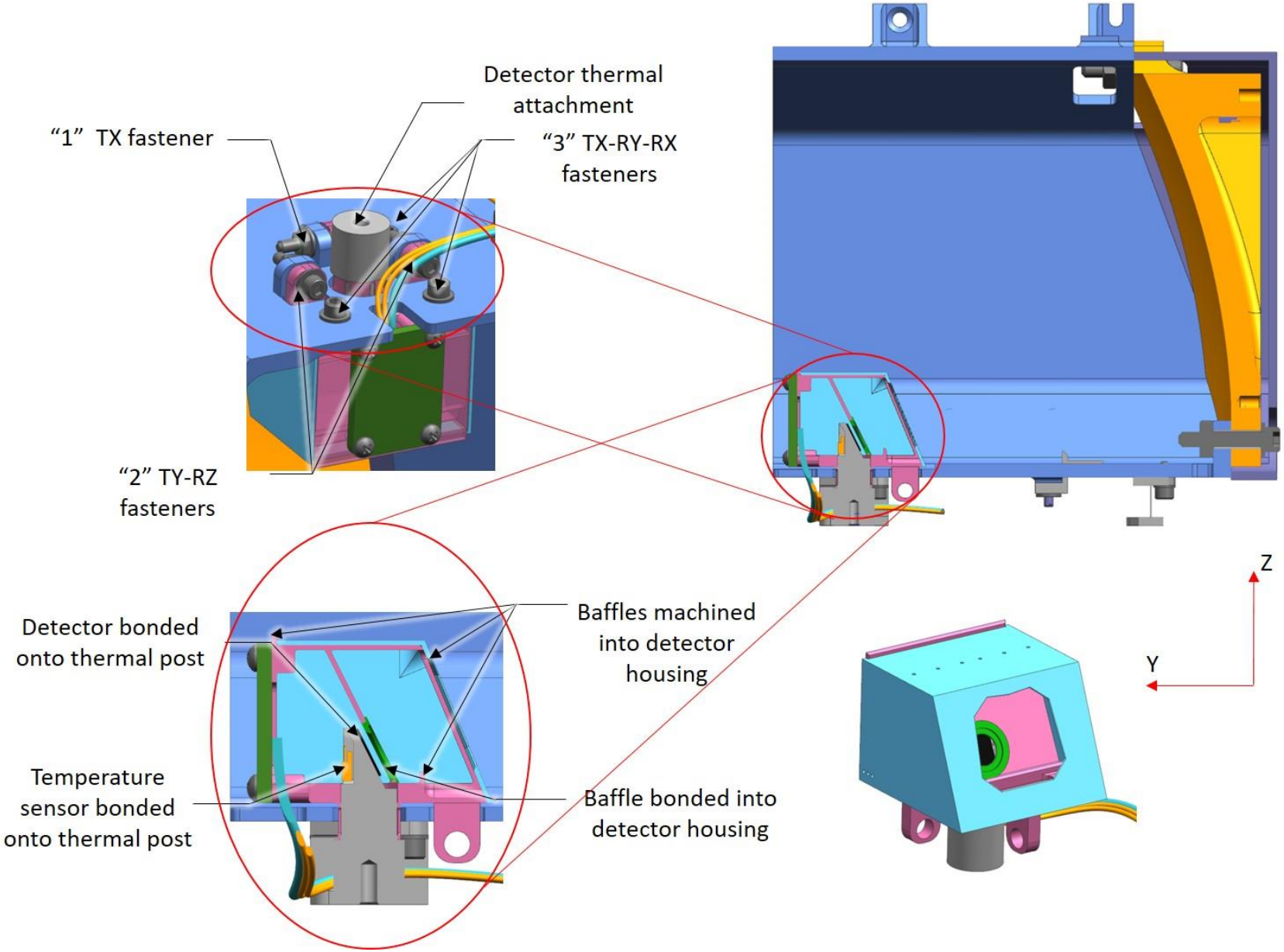
Receiver optomechanical design

Mechanical design:





Mechanical design:



Conclusions and perspectives

- Design of a SWIR optical receiver based on an aluminum paraboloid mirror focusing incoming light onto a single pixel detector.
- Main challenge: design optimization (detector diameter, focal length, vanes/baffles) to minimize the overall uncertainty on the measurements.
- Next steps: manufacture, calibration & characterization, integration to the CubeSat.
- This will be one of the first instruments onboard a CubeSat performing science measurements beyond low Earth orbit and the first planetary mission to measure reflectance using active sources from orbit.

Thank you for your attention!

Appendices

Stray light – Model limitations

- **This includes only 2 levels of scatter (any ray which attempts to scatter a 3rd time is stopped)**
  - This is not a major limitation, since the energy remaining in such a ray will be quite small
- **The number of rays incident on the system is approximately 2 rays per sq mm**
  - Since all relevant structures are at least 2.5mm in the smallest dimension, this should be adequate
- **BSDFs are always approximate, even well characterized surfaces like Z306 can vary by nearly a factor of two between various measurements**

PST theory

- **The PST is the ratio of the average detector irradiance to the incident irradiance, computed as a function of angle:**

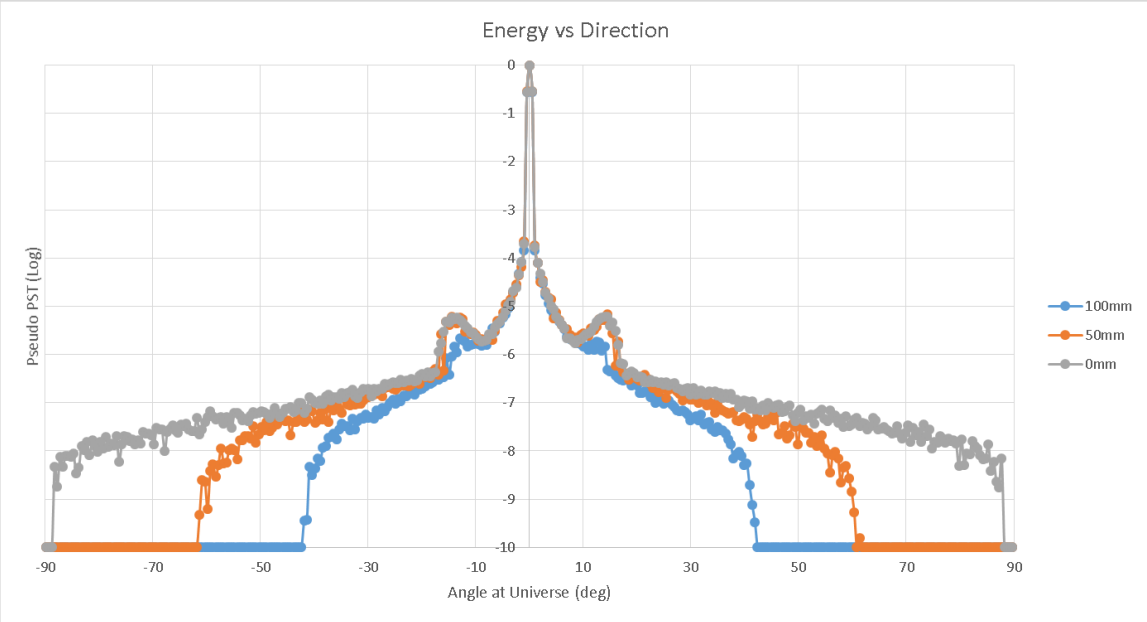
$$PST(\theta,\phi) = \frac{E_{det}(\theta,\phi)}{E_{inc}(\theta,\phi)} = \frac{E_{det}(\theta,\phi)}{P_{inc,norm} \cdot \cos(\theta) / A_{entrance}}$$

- **The source irradiance at normal incidence is typically set to unity.**
- **This PST can be used as a transfer function: the total amount of light (stray or otherwise) reaching the focal plane is**

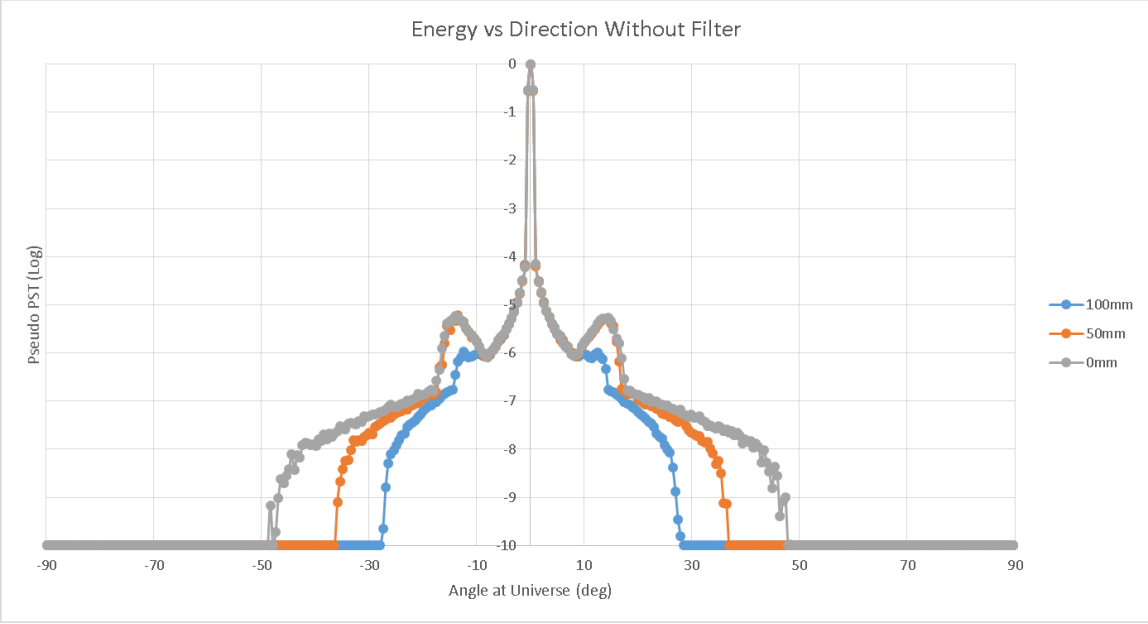
$$P_{det}(\theta,\phi) = E_{inc}(\theta,\phi) \cdot PST(\theta,\phi) \cdot A_{det}$$

Effect of extended baffles and filter on PST

With Filter

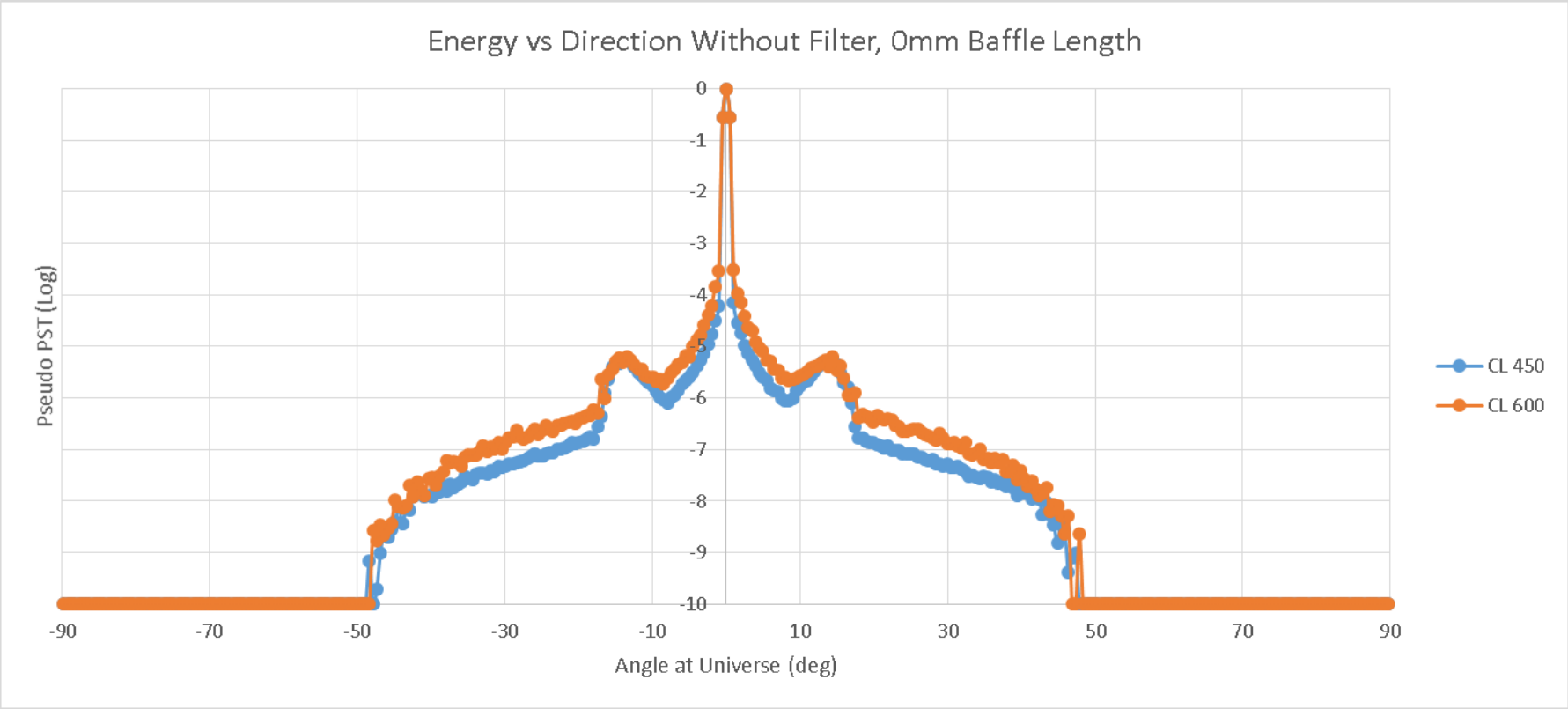


Without Filter



Contamination effect on the PST

- **Percent Area Coverage (PAC) = percent of surface which is obscured by particulates**
- **CL 450 = 0.164 PAC**
- **CL 600 = 0.696 PAC**



Manufacture tolerances

3D decenter of Detector: 0.5 mm

3D decenter of mirror: 2.0 mm

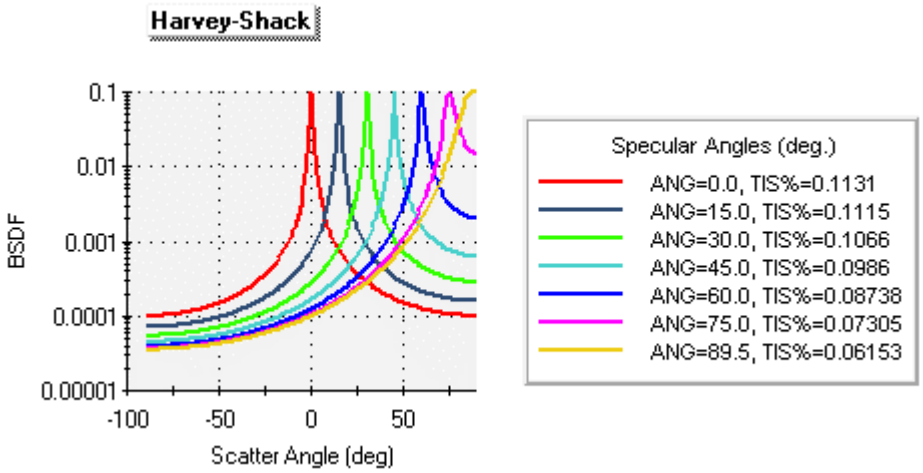
Mirror focal length 1.0 mm

Mirror tip/tilt: 0.05 rad

Detector tip/tilt: 0.05 rad

Scatter model

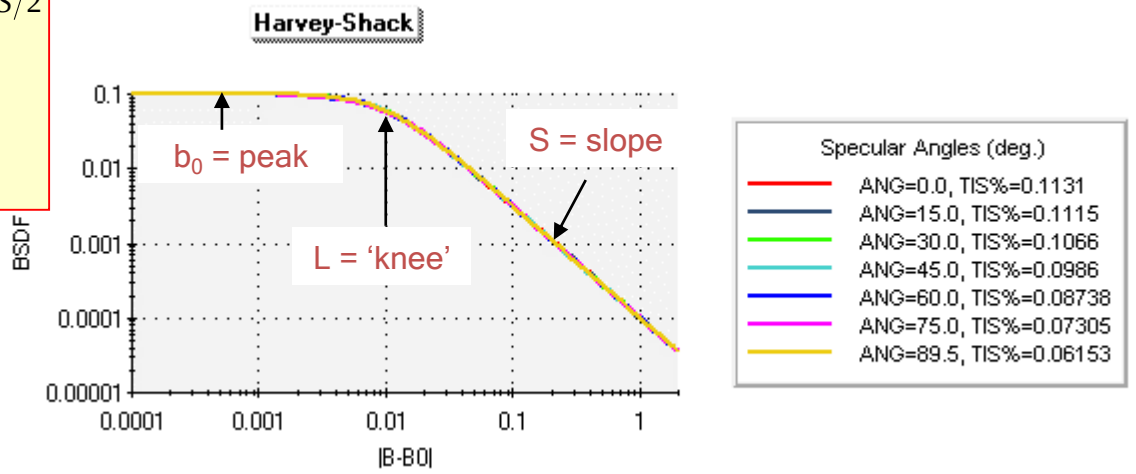
- **Empirically derived from measurement**
- **No intrinsic wavelength dependence**
- **Lorentzian around specular ray**
- ***Linear-shift invariant*: BSDF depends on the difference (β-β_0) between the specular and scattered rays**



Harvey-Shack

$$BSDF(\beta,\beta_0) = b_0\left(1+\left(\frac{\beta-\beta_0}{L}\right)^2\right)^{S/2}$$

$$specular\ \ peak = b_0$$



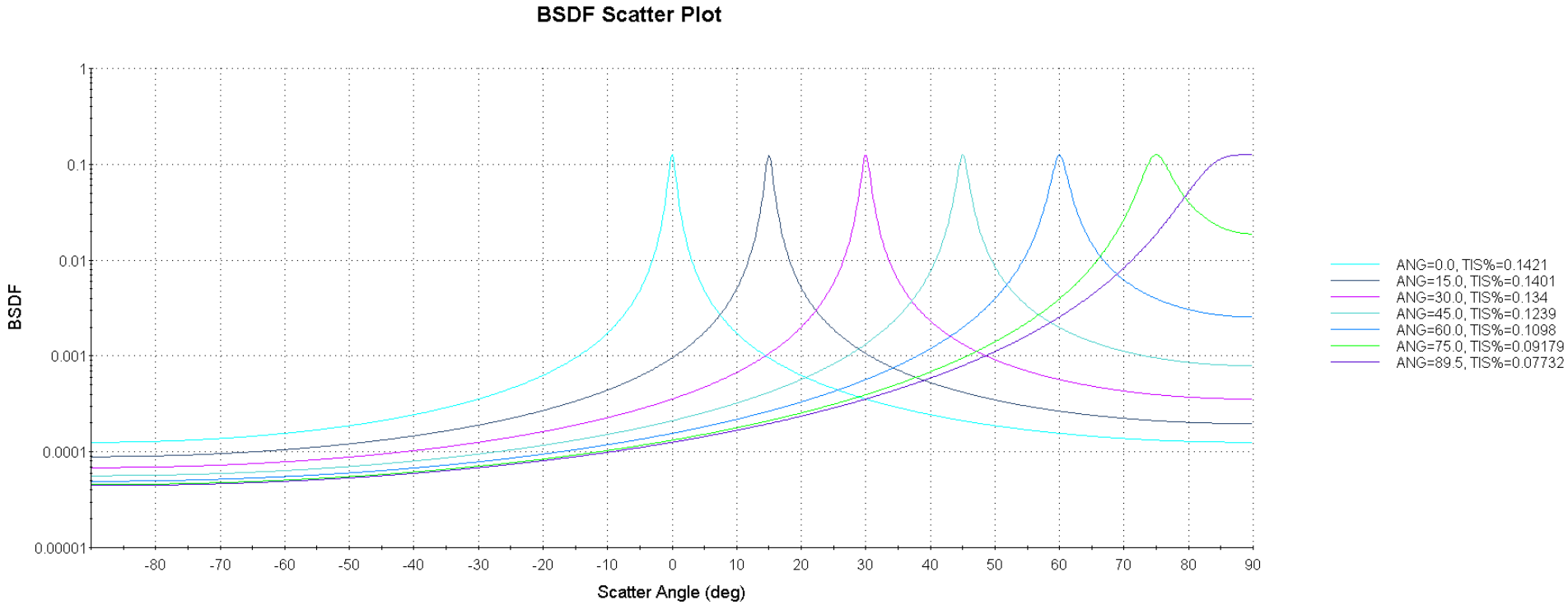
ABg

$$BSDF(\beta,\beta_0) = \frac{A}{B+\left(\beta-\beta_0\right)^g}$$

$$specular\ \ peak = A/B$$

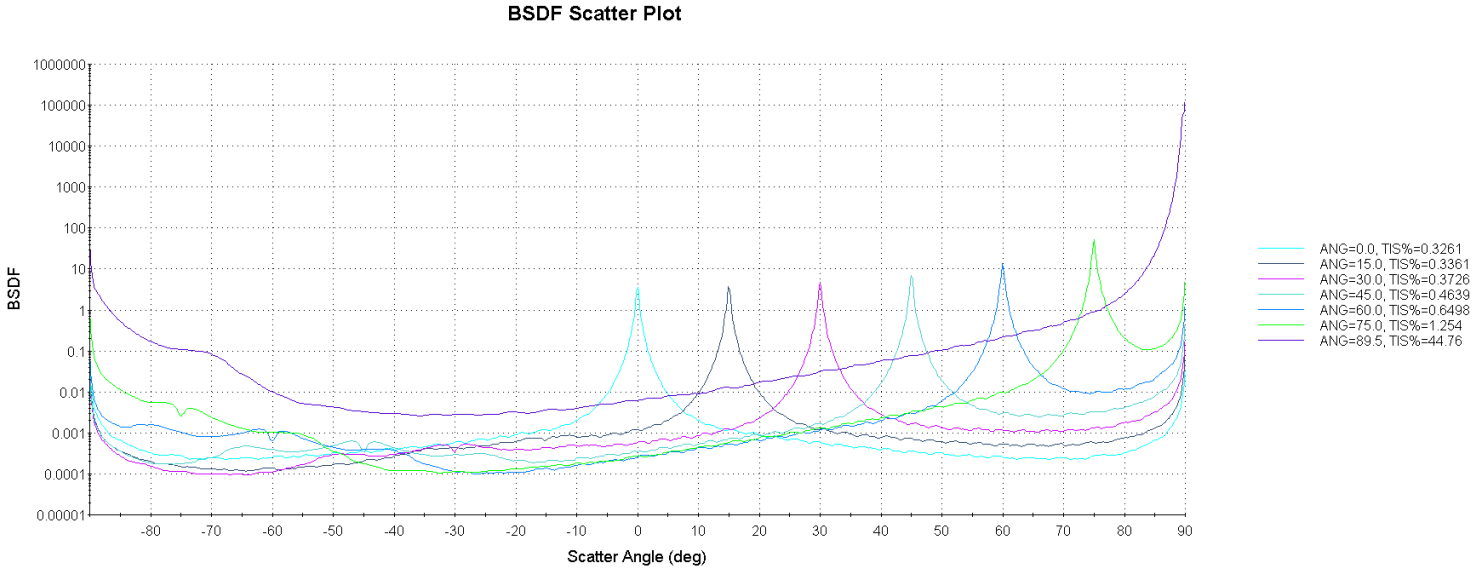
Scatter model

Mirror 30Å Surface Roughness

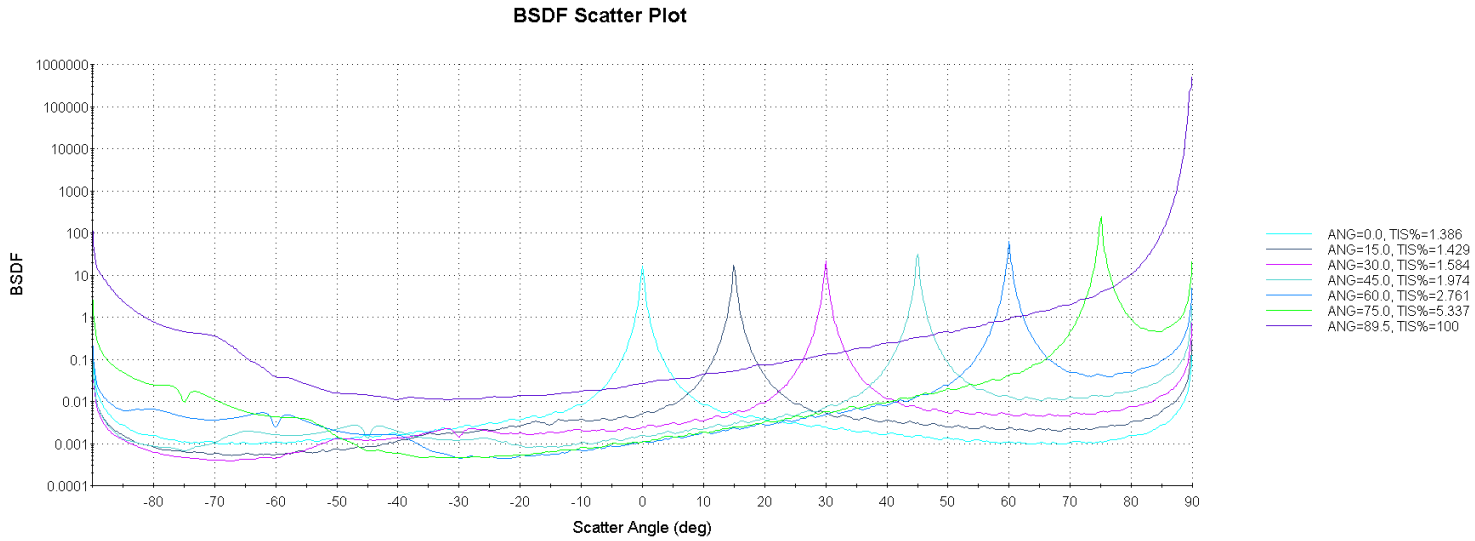


Scatter model

Mirror Particulates CL450

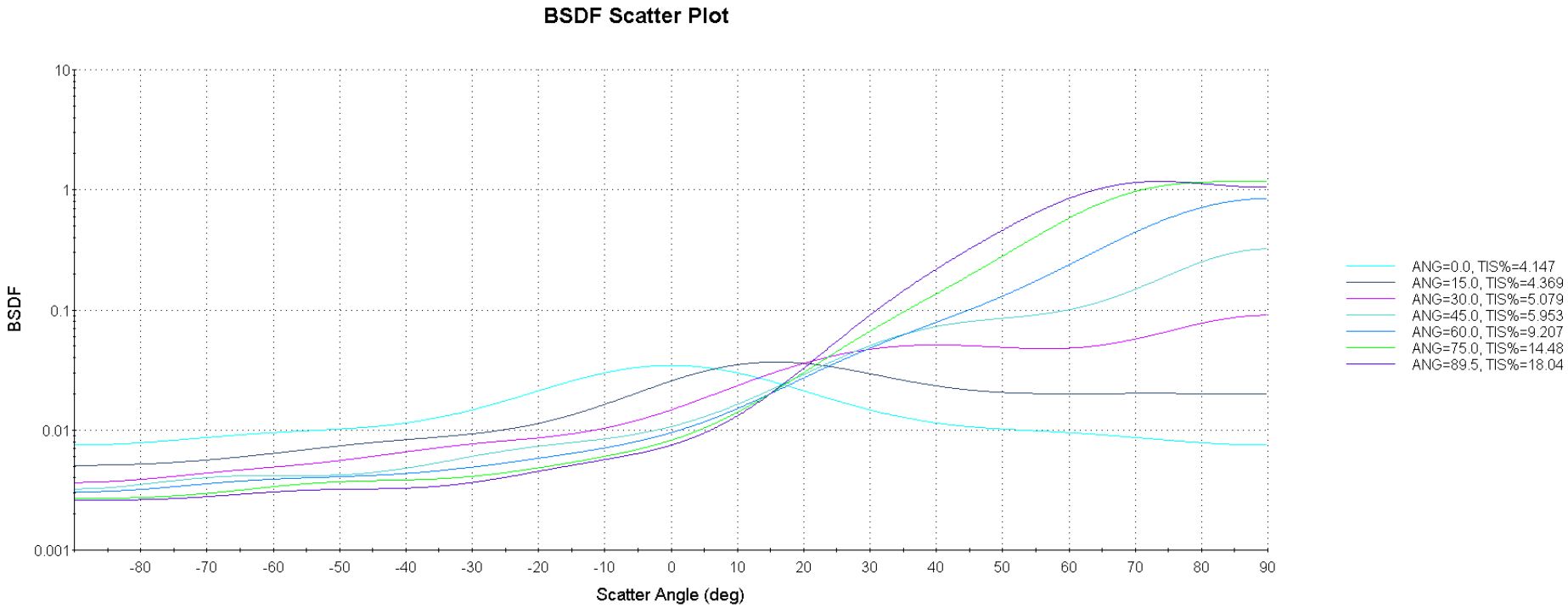


Mirror Particulates CL600

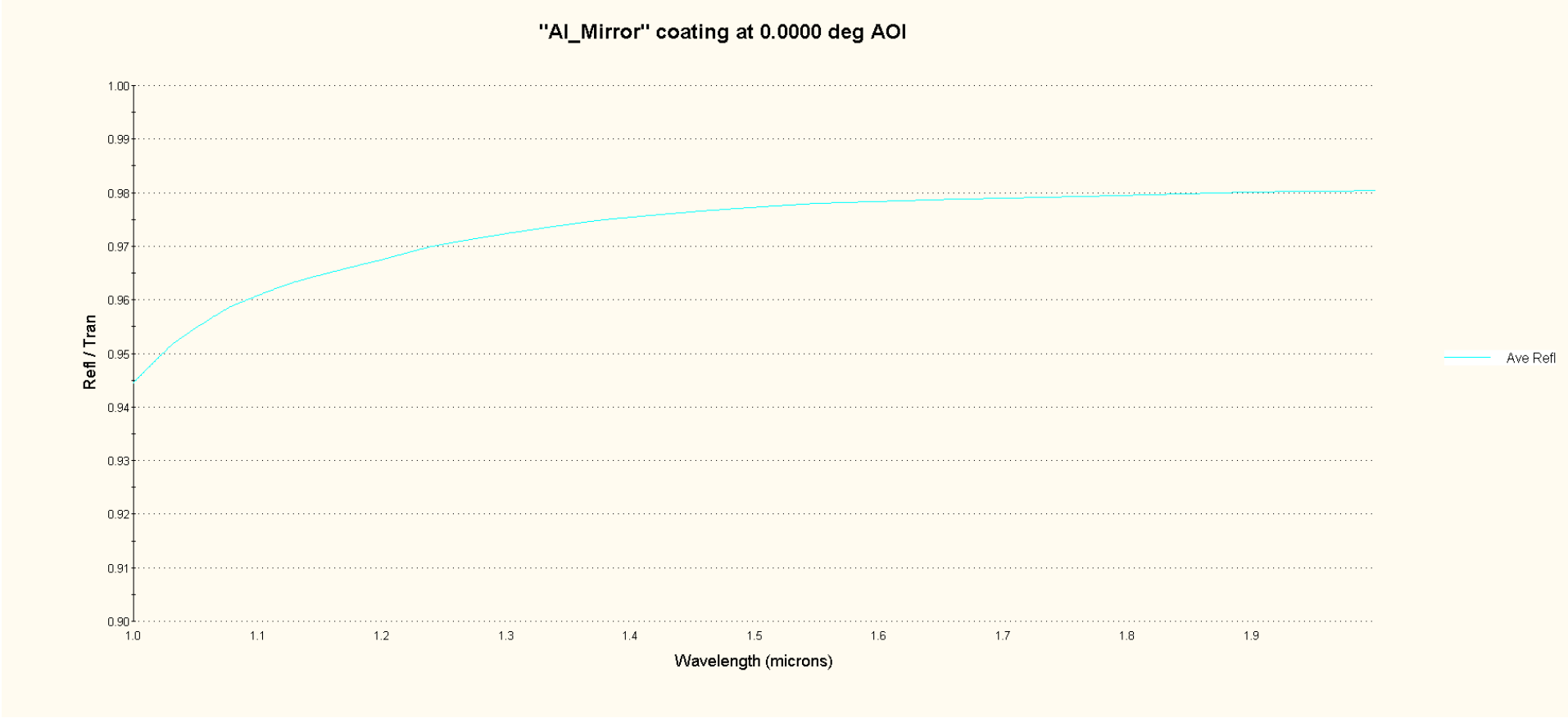


Scatter model

Z306 Diffuse Black Paint



Bare Al Coating (Mirror) - Reflectivity

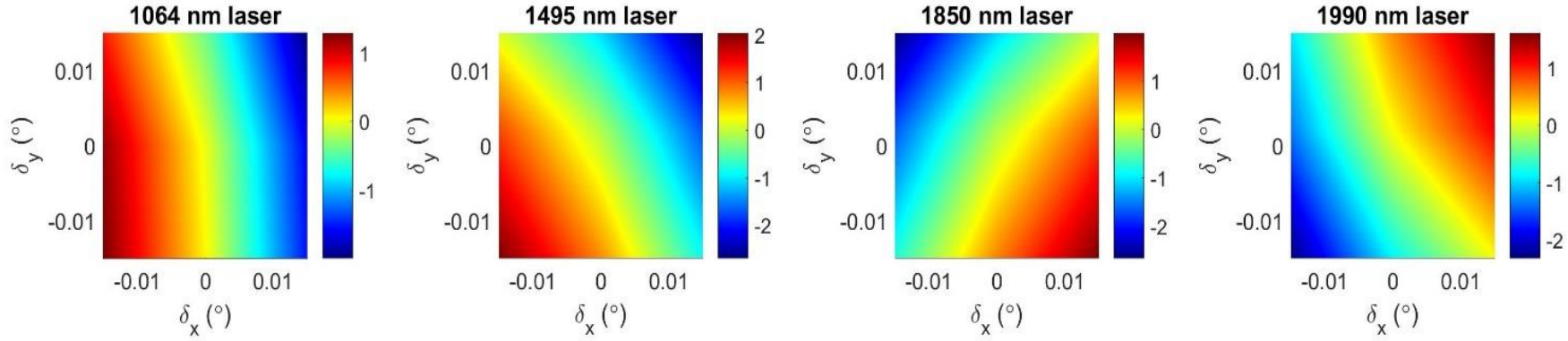


Systematic errors due to pointing instabilities

$$P_{detected,\lambda} = P_{emitted,\lambda} \times R_\lambda \times \int \mathrm{PST}_\lambda(\theta_x - \delta_x, \theta_y - \delta_y)\mathrm{LDP}_\lambda(\theta_x, \theta_y)\mathrm{d}\theta_x d\theta_y$$

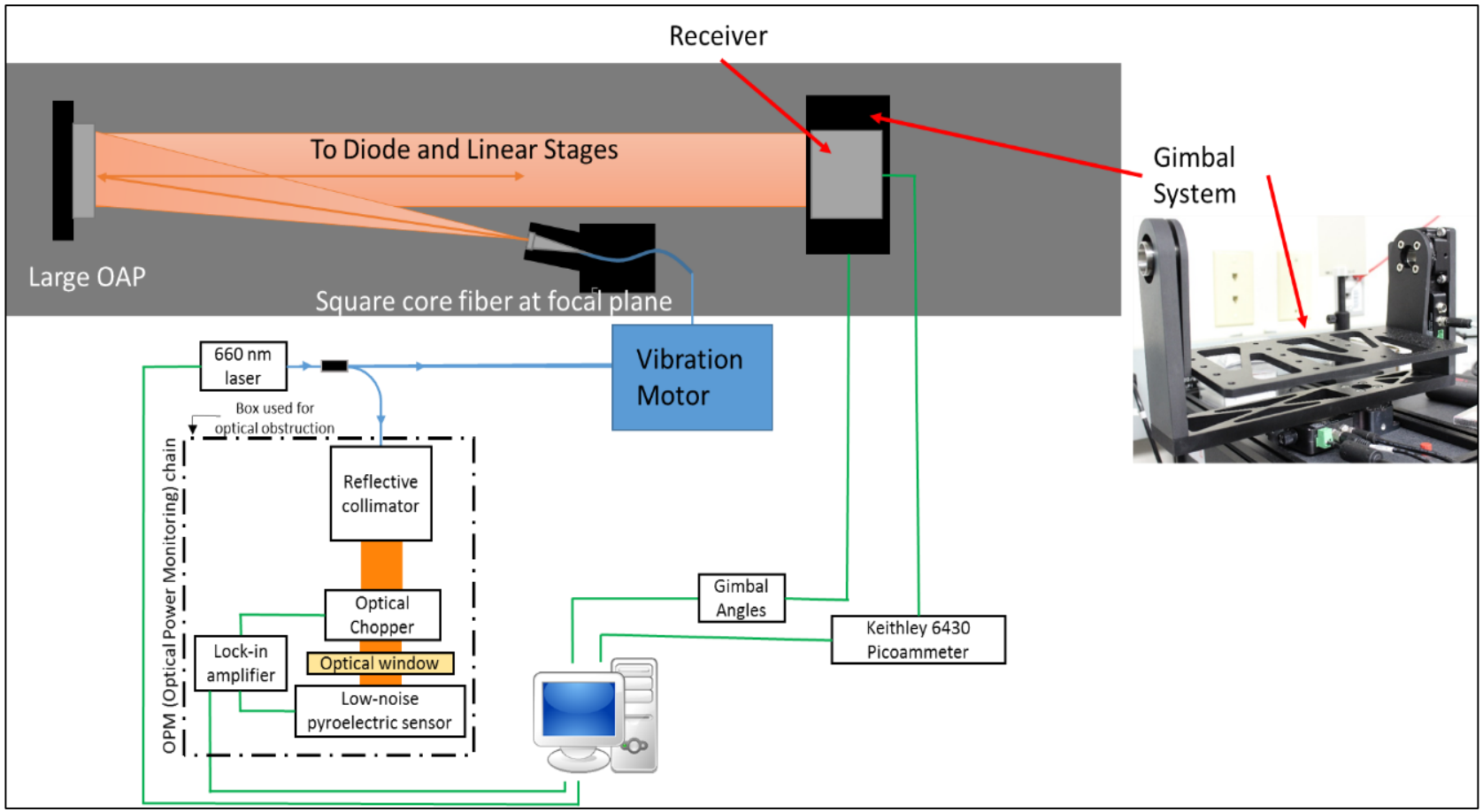
$$SE(\%) = \frac{\int \mathrm{PST}_\lambda(\theta_x, \theta_y)\mathrm{LDP}_\lambda(\theta_x, \theta_y)\mathrm{d}\theta_x d\theta_y - \int \mathrm{PST}_\lambda(\theta_x - \delta_x, \theta_y - \delta_y)\mathrm{LDP}_\lambda(\theta_x, \theta_y)\mathrm{d}\theta_x d\theta_y}{\int \mathrm{PST}_\lambda(\theta_x, \theta_y)\mathrm{LDP}_\lambda(\theta_x, \theta_y)\mathrm{d}\theta_x d\theta_y} \times 100$$

$$\Delta = max\left[\left|\frac{\int \mathrm{PST}_\lambda(\theta_x, \theta_y)\mathrm{LDP}_\lambda(\theta_x, \theta_y)\mathrm{d}\theta_x d\theta_y - \int \mathrm{PST}_\lambda(\theta_x - \delta_x, \theta_y - \delta_y)\mathrm{LDP}_\lambda(\theta_x, \theta_y)\mathrm{d}\theta_x d\theta_y}{\int \mathrm{PST}_\lambda(\theta_x, \theta_y)\mathrm{LDP}_\lambda(\theta_x, \theta_y)\mathrm{d}\theta_x d\theta_y} \times 100\right|\right]_{\forall \sqrt{\delta_x^2+\delta_y^2} \le AS}$$



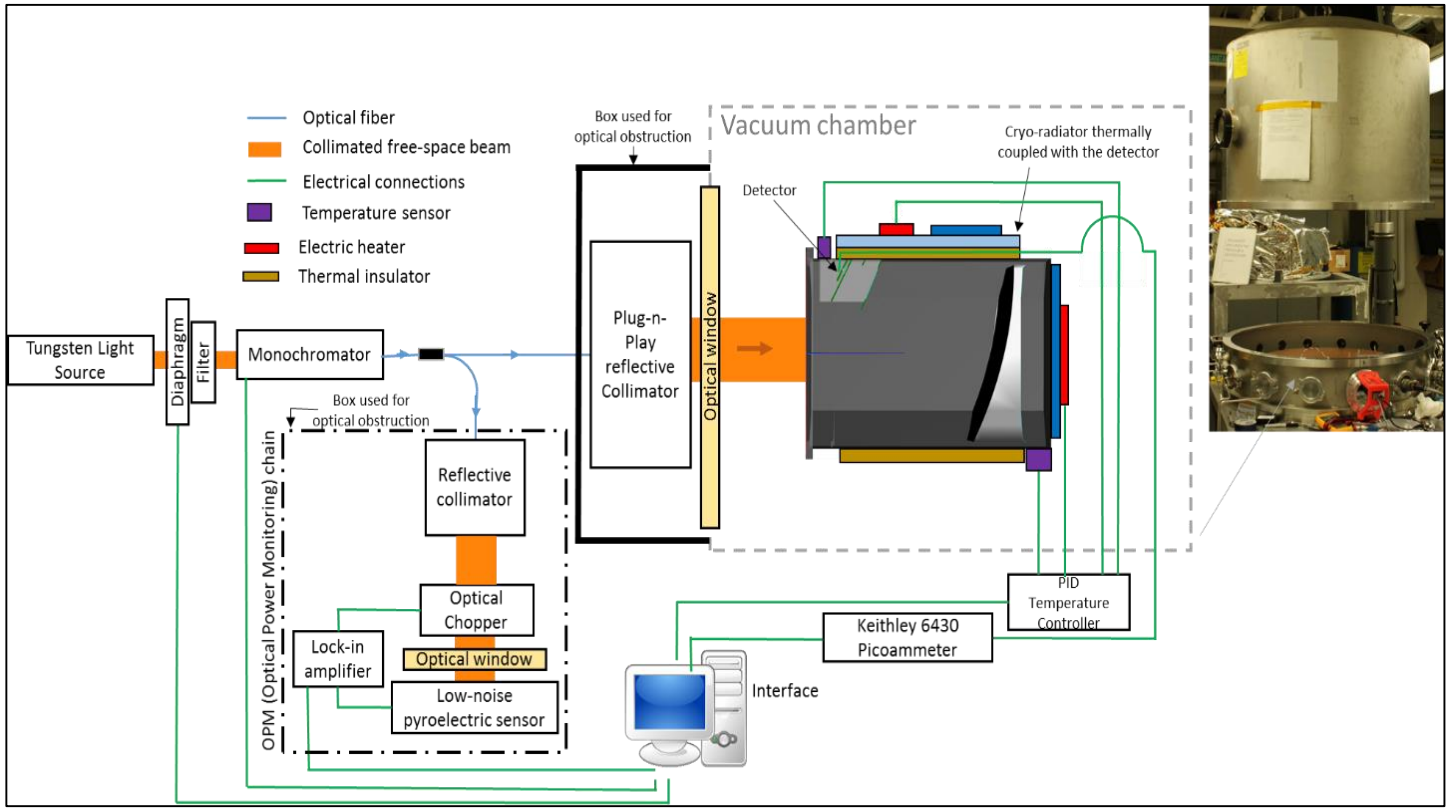
Characterization and Calibration

PST VS incidence angles at room temperature



Characterization and Calibration

- Receiver responsivity VS wavelength, detector temperature and mirror temperature
- Detector bias current VS detector temperature and mirror temperature



Characterization/calibration conditions :

- Optical power at the receiver aperture: [20, 85] nW
- Operating temperature of the detector: -65 °C
- Operating temperature range of the receiver structure: [-65,7] °C
- Vacuum of 10^{-5} Torr